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AUTHOR(S): ERIC M. JONES

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ESTIMATES OF EXPANSION TIME SCALES

by

Eric M. Jones
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Monte Carlo simulations of the expansion of a space-faring civilization show that descendants of that civilization should be found near virtually every useful star in the Galaxy in a time much less than the current age of the Galaxy. Only extreme assumptions about local population growth rates, emigration rates, or ship ranges can slow or halt an expansion. The apparent absence of extraterrestrials from the solar system suggests that no such civilization has arisen in the Galaxy.

"I see that the valleys are thick with people and even the uplands are becoming crowded. I have selected a star, and beneath that star there is a land that will provide us with a peaceful home."

Ru, Traditional Founder of Aitutaki
in the Cook Islands
(Buck 1938)

I. INTRODUCTION

An important part of the question, "Where are they?" is the question "Could they have gotten here yet?" If we imagine a spacefaring civilization arisen a billion years ago and a thousand parsecs from Earth, what are the odds that the descendants of that civilization would have established settlements in the solar system before now? The answer, I believe, is that, if such a civilization had arisen and if interstellar travel is practical at a few percent of light speed, it is virtually certain that the solar system would have been settled by non-natives long ago. Unless we discover that interstellar travel is impractical, I conclude that we are probably alone in the Galaxy.

We know nothing of any extraterrestrial civilization. If we assume some have existed, it is also reasonable to assume that at least some would be as inquisitive and as eager for adventure as humanity (Hart 1975). It would take but one such species to fill the Galaxy.

Humanity has a history of expansion into available areas on Earth. If we examine our past we can estimate how long it might be before humanity would expand throughout the Galaxy. If that time is greater than a few billion years, we would conclude that the question "Where are they?" isn't very meaningful. But if the time is less than a billion years or so, the apparent absence of extraterrestrials from the solar system is significant.

I estimate that if we develop the technical means for practical interstellar travel, humanity and its descendants will fill the Galaxy in a relatively brief time--10^8 years at most (Jones 1976, 1978). This estimate is based on assumptions about local rates of population growth, the rate at which emigrants leave one place for another, and on the choice of a mathematical model. The choices are debatable. Newman and Sagan (1978), in a widely distributed preprint, have argued for very low rates and for a different mathematical model. They estimate that the expansion time--the time to fill the Galaxy--exceeds 10^9 years. Let us examine the expansion/settlement process and the choice of rates. Afterwards, we will briefly discuss the mathematical models and, finally, discuss estimates for the expansion time.

II. HUMAN EXPANSION

Homo sapiens seems to have begun in East Africa within the past hundred thousand years. Perhaps from earliest times humans have lived in small gatherer/hunter bands which diffused throughout the Old World (Africa, Europe, and Asia). The dispersal across the Old World was undoubtedly unplanned. A band might chance to move a little further from East Africa because of movement of game, local climate changes, population pressures, warfare, disease, or natural disaster. The decision to move was made within the band (perhaps not even consciously), but the net result of millions of such decisions was that our ancestors, members of a clever and adaptable species, inhabited all parts of the Earth that were physically accessible to them before the rise of agriculture some ten thousand years ago (Davis 1974). Although humanity spread across the face of the Earth, the population increased only slowly. The rate of increase during humanity's gatherer/hunter existence has been estimated to have been only .0015% per year (Coale 1974). The available technologies could support only a very modest growth rate.

Within the past ten thousand years, the idea of agriculture arose independently at several places. With agriculture came an explosion of technological development and social institutions and a gradual end to the gatherer/hunter existence. Agriculture produced food in abundance and the new social institution provided for its distribution. The population grew and concentrated in villages, towns, and cities. Between 8000 B.C. and 1 A.D. the population growth rate may have been 0.4% per year (Coale 1974).

Although humanity had largely given up the gatherer/hunter existence, there were still reasons to move. Curiosity, food shortages, overcrowding, war, religion, politics, and countless other factors motivated countless emigrations. Some of the post-agricultural settlement ventures have been conducted by political institutions--notably the European colonies in North America. These were true colonies rather than settlements in that the sponsoring institution maintained political control.

There have been two factors which have tended to assure that human settlement has largely remained a process driven by the decisions of individuals and/or small groups. First, even when ocean-going vessels were needed for transportation, they have never been so expensive that large institutions could control the means of emigration. Second, transportation and communication were slow enough that control of emigration or immigration could not be maintained for long. Human institutions seem not to be able to maintain control from a distance. Local institutions evolve to meet local needs. Colonies become independant communities after they achieve self-sufficiency.

We have spread across the face of Earth and planted permanent, self-sufficient communities on all but the most inhospitable lands. Of places on Earth, only the ocean floor remains to be settled. We have no other place left to go but into space.

III. SETTLEMENT OF THE SOLAR SYSTEM

In the near term, we will colonize rather than settle space. Proposed large orbital habitats (O'Neil 1974) and their support technologies could be established only at enormous expense. Only the largest of human institutions could conceivably pay the estimated $\$10^{11}$ cost of establishing the first orbital community of 10^4 colonists. Such an enormous enterprise may never be attempted. However, unless we abandon space ventures entirely, economic, scientific, and political justification should exist for establishing permanently manned facilities in space and, possibly, smaller installations on the surfaces of the rocky planets and moons.

The enormous cost of lifting mass from the surface of Earth and the other large bodies in the solar system will probably guarantee that the space-living population will grow slowly <u>and</u> that efforts will be made to make the orbital facilities self-sufficient in order to reduce the costs of resupply.

Gradually, the space-living population and the technology base in space will increase. Habitats built from asteroidal or lunar materials will house small communities. Clusters of communities may occur near raw materials (the Earth-Moon system, Mars, Jupiter, the Asteroidal zone), but humans will be scattered throughout the solar system, living in habitats connected by vast communications and data networks and separated by small energy differentials.

IV. INTERSTELLAR SETTLEMENT

Once a sufficient base of population and technology is established in near-Earth orbit, the settlement of the solar system should proceed fairly steadily. Solar system distances are short enough that no journey would take more than a few years; the energy expenditures for travel would be modest. And, as in the pre-agricultural expansion of humanity across the face of the Earth, the crucial resources--sunlight, carbon, water, etc.--are accessible throughout the solar system, particularly among the asteroids and in the Jovian and Saturnian systems.

The next step outward, the step into interstellar space, introduces a new factor into the expansion/settlement process: extreme separation of potential settlement sites. Unless we assume that human communities can flourish in interstellar space (Dyson 1979), the settlement sites will be orbits close enough to stars that starlight can be used as the principle energy source and that a dependable supply of raw materials in the form of asteroids, comet-nuclei, moons, and gas giant atmospheres is near at hand. If we assume that settlements will be established in orbit about single, late-type stars and that the interstellar vessels move at about one-tenth light speed, the settlements will be separated, on the average, by 4 parsecs and journeys of 125 years (Jones 1978).

In no previous human expansion has the average journey been life long. Even though the interstellar vessels may house large communities of emigrants (perhaps 10^4 or 10^5 per vessel) and resemble the interplanetary habitats in which the emigrants and their ancestors had lived for centuries, millenia, or longer, and even though communications could be maintained with the home system and with the destination, the emigrants would be effectively isolated from the rest of humanity by distance and by communications time lags of up to 12 years! It is difficult to imagine the maintenance of interstellar colonies. Even if the journeys were made in suspended animation, a 125-year time gap could be a serious problem for colonial administrators. It seems evident that any human settlements established outside the solar system will, of necessity, be independent, self-sufficient communities.

There was an analagous human migration, recorded in part in the oral history of the Polynesian peoples (Buck 1938). In seemingly extraordinary feats of navigation, the widely separated islands of the Pacific were settled, perhaps in several episodes, by agricultural/fisher peoples of Asiatic origin.

Although there is considerable debate on many details of the settlement of Polynesia, it appears that the Pacific was settled long after the rest of the world. Settlement of Easter Island, 1100 miles from the nearest land (Pitcairn), occurred only a few hundred years before the arrival of Europeans.

The Polynesians were superb navigators. They used the stars, winds and currents, and observations of migratory birds and clouds as they crossed hundreds of miles of open ocean between island groups. The initial discovery of an island may have involved some luck (good or ill) but, once found and reported, the islands were not lost.

The great Pacific distances required that the emigrants carry with them supplies for voyages of up to three or four weeks as well as everything they would need when they arrived at their destination. Along with themselves and their culture, they brought foodplants (notably coconut, bananas, and breadfruit) and domestic animals (dogs, fowl, and pigs). Contact was maintained over long periods with other parts of Polynesia, but cultural and language divergence was certainly evident by the time the Europeans arrived (Buck 1938). The Polynesian peoples and culture spread throughout the Pacific because the necessary technology was available. In some sense it was the technology that spread. Similarly, in the interstellar case, cultural and even genetic drift can be expected. If human descendants fill the Galaxy, they may well be members of diverse species and cultures but their biologic and technologic heritage will have originated in the solar system.

V. MATHEMATICAL MODELS

The dispersal of a tracer gas in a background gas is described by the diffusion equation. Each molecule of tracer moves an average distance, called the mean-free path, between collisions with the background gas. The collisions are isotropic; there is no preferred scattering angle. A requisite for application of the diffusion equation is that the mean-free-path is short compared with any gradient length scales; the density of tracer particles cannot change by large factors over a mean-free path.

There are clearly physical situations to which the diffusion equation does not apply. An obvious example is a chemical explosion in which the explosive products move outward at high speed, forming a shock wave. At the shock front the gradient length scale is comparable with the mean-free path, and the approximations which lead to the diffusion equation break down.

The dispersal of plant and animal species has been successfully treated with the diffusion equation (for example, Newman 1980). The modifications necessary to extend the diffusion model to living creatures are the addition of a source term (the population increases) and interpretation of the mean-free-path as the average distance between an individual's place of birth and the birthplace of offspring. As long as the gradient length scales remain relatively large, the modified diffusion equation is an entirely adequate description of the dispersal of life.

Newman and Sagan (1978) have attempted to apply the diffusion equation to interstellar migrations. Their equation may be written as

$$\frac{\partial P}{\partial t} = \alpha P \left(1 - P/P_s\right) + \gamma \Delta^2 \frac{\partial}{\partial x} \left(P \frac{\partial P}{\partial x}\right) \tag{1}$$

where

P = the population of a settlement,

P_s = the carrying capacity of a settlement,

t = time,

x = spatial coordinate,

α = local population growth rate,

γ = emigration rate, and

Δ = mean separation of settlements.

The solution to equation (1) is

$$P/P_S = 1 - \exp\left(\frac{x - \nu t}{L}\right) \tag{2}$$

where

$$L = \Delta \sqrt{\frac{2\gamma}{\alpha}} = \text{gradient length scale}$$

and

$$\nu = \Delta \sqrt{\frac{\alpha\gamma}{2}} = \text{wave speed} \quad .$$

For problems of interest the local growth rate (α) greatly exceeds the emigration rate (γ) so that $L \ll \Delta$. The clear implication is that the modified diffusion equation cannot apply to interstellar migrations.

In some ways interstellar migrations may resemble explosions. With relatively slow emigration rates the populations at neighboring settlements can differ by large factors. Spatial population gradients can be steep at the frontier and important to calculations of an accurate solution.

A more appropriate solution method is a discrete, Monte Carlo simulation (Jones 1976, 1978, 1980). Briefly, we scatter settlement sites in a test volume. We assume that local population growth is given by

$$\left[\frac{\partial P}{\partial t}\right]_L = \alpha P \,(1 - P/P_S) \quad , \tag{3}$$

that emigration is

$$\left[\frac{\partial P}{\partial t}\right]_E = \begin{cases} -\gamma P\ (1 - P/P_s) & P > P_L \\ 0 & P < P_L \end{cases} , \tag{4}$$

and that immigration from nearby settlements occurs only when $P < P_L$. Numerical experiments demonstrate that the precise treatment used to describe emigration and immigration is relatively unimportant to the solution. More details are given by Jones (1976, 1978, 1980).

VI. CALCULATIONAL RESULTS

Monte Carlo solution has been obtained under these assumptions:

1. the density of settlements is 0.0015 pc^{-3}. This corresponds to a mean separation of sites of 2.2 parsecs;
2. the ship speed (v_s) is 0.1 c = 0.03 pc yr^{-1};
3. the maximum voyage is 22 parsecs; and
4. emigrants are sent alternately to the two nearest open settlement sites ($P < P_L$).

The solutions are not particularly sensitive to the choice of a ship range unless the range is comparable to the separation of sites. If this is the case, settlement is likely not to occur; the home system and/or the first few settlements are isolated from other potential sites. The settlement wave dies off.

The solutions are presented in Fig. 1 as calculated wave speed as a function of the coefficients α and γ, both given in parts per year. The wave speed is given in parsecs per year. Newman (private communication) has shown that the Monte Carlo results are well approximated by

$$\nu = \overline{\delta r}/[(\overline{\delta x}/v_s) + (1/\alpha)\ \ln\ (2\alpha/\gamma)] \tag{5}$$

where

$\overline{\delta r}$ is the average radial distance traveled, and

$\overline{\delta x}/v_s$ is the average travel time.

Usually we can assume $\overline{\delta r} = 0.7\ \Delta$ and neglect the travel time and use

$$\nu \approx 0.7\ \alpha\Delta/\ln\ (2\alpha/\gamma) \quad . \tag{6}$$

VII. DISCUSSION

It is evident from Fig. 1 that as long as $\gamma \ll \alpha$, the wavespeed is dominated by the local growth rate (α). The evidence suggests that since the rise of agriculture the rate has exceeded 10^{-3} per year (Coale 1974). It seems likely that the very high rates experienced since the industrial/scientific revolution (1 to 2% per year) are a temporary departure from normality due to the dramatic decrease in the death rate in the past 200 years. We speculate that a more appropriate rate would be $\alpha = 10^{-3}\ yr^{-1}$.

If $\alpha \gtrsim 10^{-3}\ yr^{-1}$, it is evident that the wavespeed will exceed 10^{-4} pc yr^{-1} unless the emigration rate is less than 10^{-8}. The choice $\alpha \gtrsim 10^{-3}\ yr^{-1}$ gains some credence from the consideration that if one invokes small α to explain the absence of extraterrestrials from the solar system, then small growth rates must be invoked for <u>all</u> technological civilization.

From data given by Potter (1965), the estimated emigration rate from Europe to North America during the 18th century was $3 \times 10^{-4}\ yr^{-1}$. From data cited by Davis (1974), emigration in the period 1840 to 1930 often exceeded that value. The great Irish emigration of that period saw rates as large as 0.01 yr^{-1}! About one hundred Irish arrived at American ports each day for years on end. It seems likely that $\gamma = 10^{-8}\ yr^{-1}$ as suggested by Newman and Sagan (1978) is a gross underestimate of human emigration rates.

We have, then, a reasonable lower limit to the settlement wavespeed of 10^{-4} parsecs per year. Since the Galaxy is a thin disk about 3×10^4 parsecs in diameter, we estimate that humanity could fill the Galaxy in no more than 3×10^8 years. Because this time is short compared to the 4.6×10^9 year age of the solar system, the apparent absence of non-native civilizations from the solar system is significant. Only if $\alpha < 10^{-4}$ do the time scales become comparable.

VIII. CAVEATS

Are we alone? The settlement calculations suggest that we are. However, the calculations are based on extrapolations from our past and speculations about our future. They must be viewed with suspicion.

There are several assumptions we have made which could be drastically wrong. Foremost among these is that we assume interstellar travel is practical. Interstellar settlement will not occur on any significant scale if the voyages are very expensive. I suspect that if the labor costs exceed a few man-years per emigrant, the emigration rate will be very low, if not zero. The cost will not include the technological base. That will have to exist for its own sake. Interstellar transportation systems will have to be an outgrowth of ordinary interplanetary systems--interstellar 747's rather than interstellar Saturn V's. I suspect that the requirement that interstellar travel not be terribly expensive is not a serious prerequisite. Interstellar transportation systems may seem expensive from our perspective, but then, so would a 747 to the Wright brothers.

One further caveat needs to be mentioned. If humanity can live in interstellar space, using stars and planetary systems merely as waystations (Dyson 1979), our estimates of the settlement times may be meaningless. The diffusion equation will apply, Δ will be very small, and most importantly, the absence of obvious signs of settlements in the solar system will be insignificant.

If I were forced to bet on the question, I would bet that we are alone. But we won't have a definitive answer until we have explored a large portion of the Galaxy and found no one home.

VIII. ACKNOWLEDGMENTS

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The assistance of the staff of the National Library, Dublin, Ireland, is gratefully acknowledged. In search of an ancestor, my wife and I were directed to copies of 19th-century passenger lists. Our examination of the lists of people arriving at New York, Baltimore, and other American ports on a single day in August 1859 gave a sense of the magnitude of the Irish emigration. These lists are also available at the National Archives, Washington, DC.

I note that Peter H. Buck, whose book Vikings of the Pacific is an interesting introduction to the Polynesian migration, was Maori/Irish--hence, the product of two great migrations.

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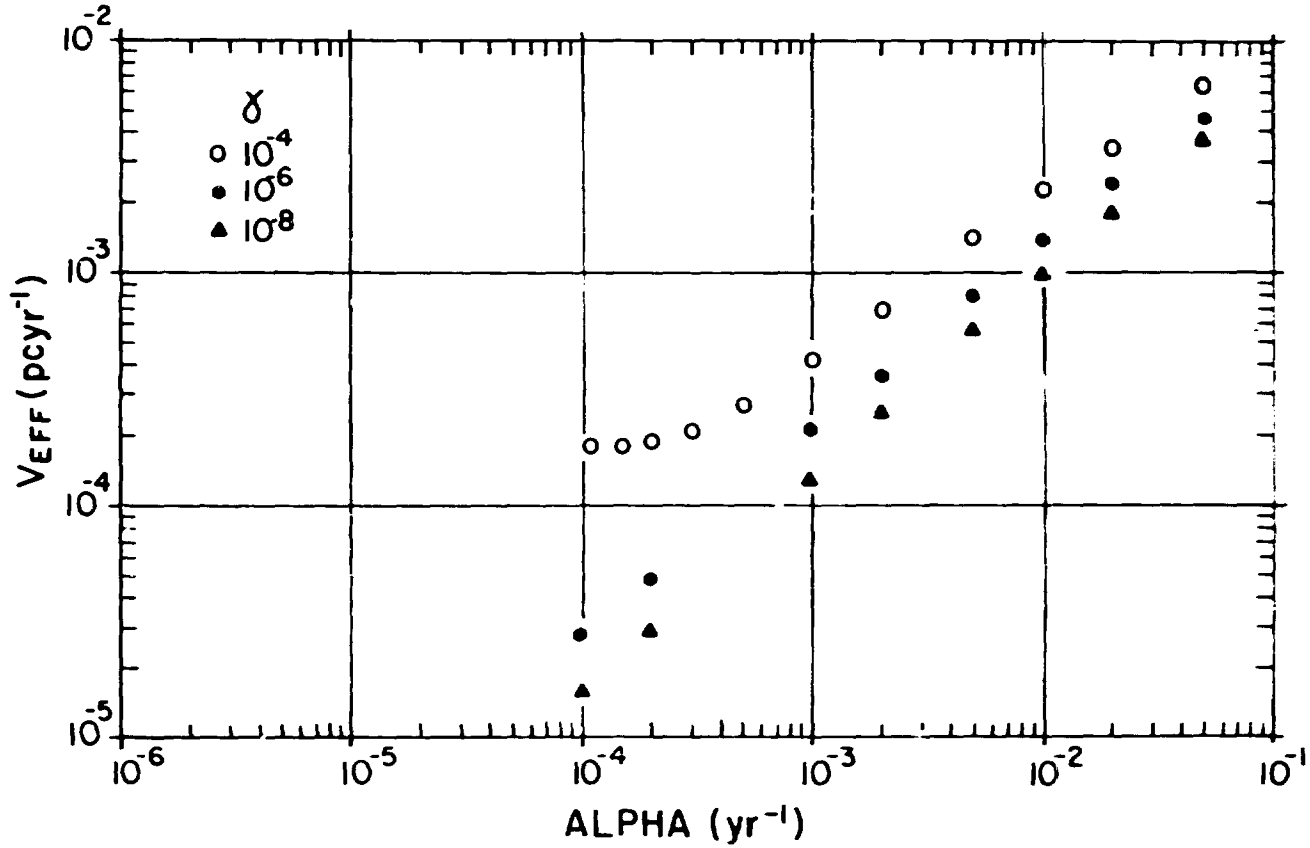
Figure Caption

Figure 1 - The wave speed calculated for human settlement of the Galaxy is plotted as a function of the local population growth rate (alpha) for three values of the emigration rate (gamma). Newman (private communication) has shown that the wavespeed is well approximated by $v = 0.7\ \alpha\Delta/\ln(2\alpha/\gamma)$, where Δ is the mean separation of settlement sites. For these calculations we assumed $\Delta = 2.2$ parsecs. The history of human migrations and population growth suggests that reasonable values of the parameters are $\alpha = 10^{-3}$ and $\gamma = 10^{-4}$. The calculated wavespeed is 5×10^{-4} parsecs per year and the implied time needed for humanity to settle the Galaxy is 60 million years.



γ
10^{-4}
10^{-6}
10^{-8}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
V_{EFF} (pcyr^{-1})
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
ALPHA (yr^{-1})